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# The rotation-magnetic field relation

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**Abstract.** Today, the generation of magnetic fields in solar-type stars and its relation to activity and rotation can coherently be explained, although it is certainly not understood in its entirety. Rotation facilitates the generation of magnetic flux that couples to the stellar wind, slowing down the star. There are still many open questions, particularly at early phases (young age), and at very low mass. It is vexing that rotational braking becomes inefficient at the threshold to fully convective interiors, although no threshold in magnetic activity is seen, and the generation of large scale magnetic fields is still possible for fully convective stars. This article briefly outlines our current understanding of the rotation-magnetic field relation.

**Keywords:** stars:activity, stars:rotation, stars:magnetic fields

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## INTRODUCTION

The rotational evolution of stars is the result of the complex interaction of several fundamental processes. First, the molecular cloud contracts conserving initial angular momentum spinning up the central object. Angular momentum can be stored in a disc, which may brake the rotation of the central object. After the disc is dissipated, the star can contract reaching the highest rotation rate after several ten million years of lifetime. Solar-type stars, i.e., stars with convective envelopes, start generating magnetic fields that couple to the stellar wind. The interaction between charged particles in the wind and the magnetic field generates a torque braking the star's rotation. In the case of the Sun, braking has led to a rotation rate of about 1 revolution every month.

According to the rotation-activity relation, rapidly rotating stars produce strong magnetic fields generating a strong magnetic torque that brakes the star. This leads to slower rotation, which in turn weakens the magnetic field production and braking is weakening, too. At young ages in open clusters, we observe rapidly rotating, very active stars, while the (single) field stars generally are slowly rotating and only weakly active. This means that in principle rotation and activity can tell about the age of a star [e.g., 2, 3].

The connection between rotation, stellar wind, magnetic fields, and magnetic activity is reviewed in this splinter session summary. First, we give an overview about the current picture on rotation in both clusters and the field, i.e., in young and old stars. Next, we discuss results from direct and indirect magnetic field measurements and their connection to stellar wind theory. In the last part, we give a summary on the theoretical work on magnetic field generation through stellar dynamos. Low-mass stars and in particular the regime where stars become completely convective currently present a rather puzzling picture of the connection between magnetism, activity, and rotation. Thus, low-mass stars are in the focus of our summary.

## **ROTATION**

### **Young objects**

The net effect of early stellar evolution and disc-coupling is that a star has approximately constant angular velocity for the first few Myr while it is still coupled the disc. Then it spins up rapidly once the disc dissipates, reaching maximum rotational velocity close to when it arrives on the zero age main sequence, followed by a gradual decay due to the stellar wind, lasting for the remainder of the main sequence lifetime.

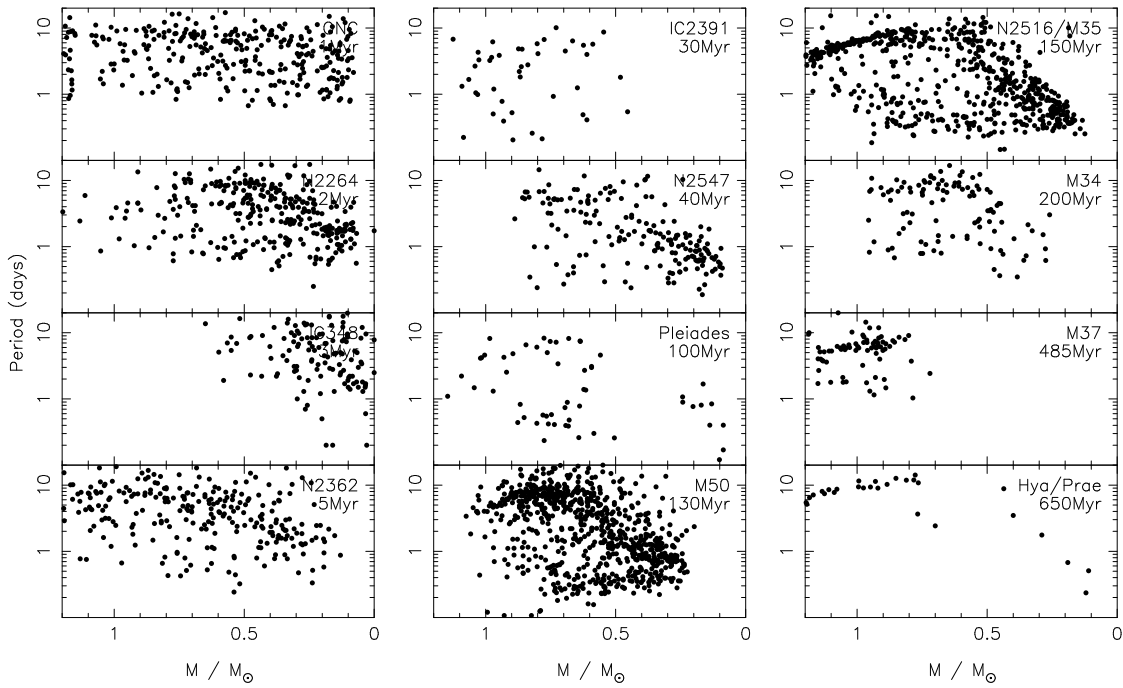
Rotational evolution has traditionally been constrained by using measurements in open clusters to provide “snapshots” during the evolution. Large samples of these are now available covering  $\sim 1 - 650$  Myr (see Fig. 1). It is becoming increasingly clear that the evolution is strongly mass and rotation rate dependent, and this has important consequences for the nature of the mechanisms governing the angular momentum losses.

In particular, unlike solar-type dwarfs, low-mass dwarfs spin up much more rapidly, appear to experience no significant angular momentum losses on the pre main sequence, and much weaker losses due to winds on the main sequence.

### **Field stars**

Early stars with no relevant convective envelopes cannot generate surface magnetic fields, they rotate rapidly during their entire lifetime. Solar-type stars with convective envelopes are strongly braked as seen above. This is consistent with observations of coronal emission, chromospheric emission, and latitudinal differential rotation, which set in exactly where stars are believed to form convective envelopes, i.e., around spectral type A7–F0. Wind braking becomes very efficient around late-F type stars, and the Sun for example has slowed down to less than  $2 \text{ km s}^{-1}$  during its lifetime.

Field stars of spectral type K and early-M typically rotate very slowly as well, although in their youth braking was probably somewhat weaker (see above). Virtually all single field K and M dwarfs, including early-M classes M0–M3, are rotating at velocities slower than about  $3 \text{ km s}^{-1}$ . Around spectral type M3.5, however, a dramatic increase in rotation rate is observed. This threshold coincides with the mass range where stars become fully convective. It appears that for some reason rotational braking becomes weaker at this boundary.

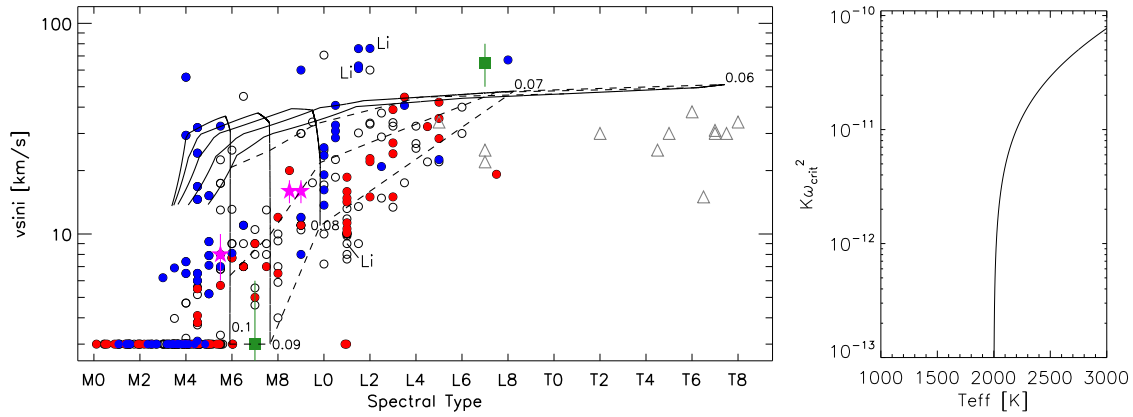


**FIGURE 1.** Compilation of  $\sim 3000$  rotation period and  $v \sin i$  measurements for open clusters at ages 1 – 650 Myr and masses  $< 1.2M_{\odot}$ . Masses were derived assuming cluster ages given in each panel. Distance and reddening are from the literature using  $I$ -band absolute magnitudes and NextGen stellar models of Baraffe et al. [1]. For the (numerous) appropriate references, please see Irwin [13].

Fig. 2 shows a compilation of (projected) rotational velocities  $v \sin i$  in objects of spectral classes M–T. The sudden increase of rotation rate is evident at spectral type  $\sim M3.5$ . Another important result is that braking does not completely vanish at least until spectral class L0. In the figure, members of the (statistically) young population are shown in blue and old stars in red, and the two subdwarfs shown with green squares are probably *very* old. Young objects are found predominantly in the upper part of the plot while the old sample shows slower rotation. This indicates that rotational braking still works in ultra-cool dwarfs. Solid lines in Fig. 2 show evolutionary tracks according to a modified braking law of the form

$$\frac{dJ}{dt} = -K\omega_{\text{crit}}^2\omega\left(\frac{R}{R_{\odot}}\right)^{0.5}\left(\frac{M}{M_{\odot}}\right)^{-0.5}. \quad (1)$$

Here,  $K\omega_{\text{crit}}^2$  was scaled according to the right panel in Fig. 2; braking is weaker at lower temperature [see 25]. A viable explanation for this may be the weaker coupling of magnetic field lines (which still exist) to the atmosphere that is becoming more and more neutral. Rotational braking in fully convective field stars and brown dwarfs appears to be so weak that after a few billion years the distribution of rotational velocities can tell a lot about their angular momentum evolution and the underlying processes, magnetic fields and (sub)stellar winds.



**FIGURE 2.** *Left:* Rotational velocities of M–T type objects. Circles are from Reiners & Basri [24, 25], Delfosse et al. [9], Mohanty & Basri [21] (blue: kinematically young, red: kinematically old); triangles from Zapatero Osorio et al. [33]. Magenta stars indicate the three members of LHS 1070 [26], filled green squares the two subdwarfs 2MASS 0532+8246 and LSR 1610–0040 [22]. Solid lines mark evolutionary tracks for objects of 0.1, 0.09, 0.08, and 0.07  $M_{\odot}$ , dashed lines mark ages of 1 and 10 Gyrs (from upper left to lower right). *Right:* Scaling of the magnetic wind-braking with temperature in Eq. 1.

## MAGNETIC FIELDS

The discovery of X-ray emission from the brown dwarf LP944-20 [28] provided the first direct demonstration of magnetic activity in the substellar regime. Subsequent X-ray,  $H\alpha$ , and radio observations revealed that low-mass stars and even brown dwarfs ubiquitously generate magnetic activity. No break is observed at the boundary to full convection, but chromospheric activity weakens after spectral type about M7 [21, 32, 29, 25], an effect that may be due to decreasing fractional ionization [20]. Quiescent activity and flaring are still observed in even cooler objects [e.g., 11, 17, 25, 27]. About 10% of ultracool dwarfs in the range M7–L4 produce both quiescent and flaring radio emission, with inferred field strengths of 0.1–3 kG and covering fractions of order unity [5], and it likely correlates with rotation velocity [7]. At the same time, the tight radio/X-ray correlation that exists in a wide range of stars (including the Sun) is strongly violated beyond M7, roughly the same regime where chromospheric and coronal emission become weaker. Equally important, several ultracool dwarfs have been observed to produce periodic radio emission and  $H\alpha$  emission. This emission may carry information about the field topology. In general, radio observations suggest that a low multipole, large-scale field configuration is the best explanation for the observed variability [6, 12].

Activity indicators like X-ray,  $H\alpha$ , and radio emission provide strong constraints on the magnetic flux depending on the mechanism that generates the observed emission. Direct measurements of magnetic fields in M dwarfs through Zeeman splitting of atomic lines were carried out by Johns-Krull & Valenti [14], results from a re-analysis with a multi-component fit are given in Johns-Krull & Valenti [15]. In late-M dwarfs, however, atomic lines become rare and more and more blended so that molecular Zeeman diagnostics would be useful, and Valenti & Johns-Krull [30] suggested that FeH could be a good indicator of magnetic flux. Reiners & Basri [23, 24] developed a method to mea-

sure magnetic flux through FeH and did so in a sample of M3–M9 dwarfs. They found that the relation between magnetic fields and (chromospheric) activity is intact through the entire M spectral range; the most active M stars exhibit magnetic fields on the order of a few kG. Thus, the lack of rotational braking in mid- to late-M dwarfs cannot be a consequence of weaker magnetic fields. Fully convective stars obviously find a way to efficiently generate magnetic fields.

## MAGNETIC FIELDS AND WIND BRAKING

How does the magnetic field connect to rotation? When a rotating star drives an outflow that is well-coupled to the stellar magnetic field, the wind and magnetic field conspire to extract angular momentum from the star. This happens because, as wind material leaves the stellar surface and tries to conserve its own angular momentum, it lags behind the star in a rotational sense. Thus, the magnetic field connecting the stellar surface to the outflowing wind is bent backwards with respect to the stellar rotation. This imparts a torque, which acts to give "extra" specific angular momentum to the wind, removing it from the star.

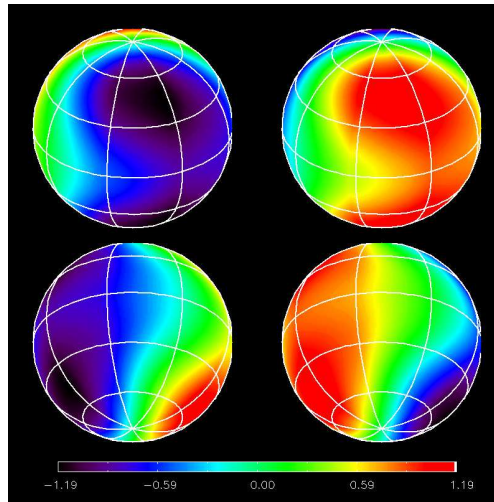
A method for calculating this stellar wind torque dates back to Weber & Davis [31] and Mestel [19], and magnetic stellar wind theory is still an active research topic. A generic result is that the torque can be written  $\tau = \dot{M}_w \Omega_* r_A^2$ , where  $\dot{M}_w$  is the mass loss rate in the wind,  $\Omega_*$  is the angular spin rate of the star, and  $r_A$  is sometimes called the "magnetic lever arm" in the flow. In a one-dimensional flow,  $r_A$  is the Alfvén radius, the radial location where the wind flow speed equals the magnetic Alfvén wave speed.

We can quantify the efficiency of angular momentum extraction by dividing the stellar angular momentum by  $\tau$ , which gives a characteristic spin-down time

$$t_{\text{sd}} = k^2 \left( \frac{R_*}{r_A} \right)^2 \left( \frac{M_*}{\dot{M}_w} \right), \quad (2)$$

where  $k$  is the "mean radius of gyration" (in main sequence stars, typically  $k^2 \sim 0.1$ ) and  $R_*$  and  $M_*$  are the stellar radius and mass. Note that the first two terms on the right-hand-side are dimensionless. The last term has the units of time and represents the mass loss time for the star. In the solar wind, for example,  $r_A/R_* \sim 10$  [e.g., 16]. Thus the angular momentum loss in magnetic stellar winds can be very efficient in a sense that the spin-down time can be much shorter than the mass loss time.

This is an elegant result, but the difficulty lies in calculating the effective  $r_A$  for an arbitrary star and a realistic (3-dimensional) wind. Our understanding of the observed evolution of stellar spins depends on this calculation of the torque. Recent work by Matt & Pudritz [18, and see contribution in these proceedings] emphasizes that, while there is still no adequate theory for predicting how the wind torque depends on stellar mass and age, significant progress can be made with the use of numerical simulations.



**FIGURE 3.** Radial component of a magnetic field of geometry type S1.

## STELLAR DYNAMOS

### Overview

The solar activity cycle is believed to be the result of a dynamo process either in the convection zone or the stably stratified layer beneath it. The original model was an  $\alpha\Omega$  dynamo in the convection zone generating a predominantly toroidal and axisymmetric magnetic field. Problems with flux storage and the internal rotation pattern found by helioseismology led to a revised model where the dynamo is located at the bottom of the convection zone. That sort of dynamo, however, produces too many toroidal field belts and too short cycle periods. The advection-dominated dynamo is an extension of the  $\alpha\Omega$  dynamo where a large-scale meridional flow advects the magnetic field towards the poles at the surface and towards the equator at the bottom of the convection zone. The butterfly diagram is now the result of the meridional flow rather than a dynamo wave and the cycle time depends on the flow as much as on the dynamo number.

For stars there is no clear picture yet. One would expect stars similar to the Sun to show the same type of activity but Doppler imaging frequently finds large spots at high latitudes and both solar-type and anti-solar cycles have been found in stellar butterfly diagrams from photometry. Large polar spots can be explained as the consequence of flux tube instability in the tachocline while anti-solar butterfly diagrams could indicate a meridional flow pattern opposite to that of the Sun.

Main sequence stars with masses below  $\sim 0.3 M_{\odot}$  are fully convective, ruling out any dynamo mechanism involving the tachocline, but some sort of dynamo must still be at work. The  $\alpha^2$  dynamo, where the  $\alpha$  effect alone generates the field, is a possible mechanism. It generates completely non-axisymmetric fields that do not oscillate, so that monitoring of active low-mass stars will provide an important step towards understanding of the dynamo in these stars. At the moment, observations support neither the  $\alpha\Omega$  nor the  $\alpha^2$  dynamo: AB Dor shows pronounced differential rotation but a strongly

non-axisymmetric surface field while V374 Peg has an axisymmetric dipole geometry despite nearly rigid surface rotation [10].

## Fully convective stars

Particularly puzzling for dynamo theorists has been the finding that fully convective M dwarfs can host *large-scale* magnetic fields, even in the absence of any apparent differential rotation. Browning [8] discussed 3-D simulations of convection and dynamo action in fully convective stars, with an eye toward answering two main questions: first, how large-scale fields might be generated without a "tachocline" of shear, and second, whether differential rotation is always absent in such stars or might be maintained in certain circumstances. In this model [8], convection acted effectively as a dynamo, quickly building magnetic fields that (in stars rotating at the solar angular velocity) were approximately in equipartition with the turbulent velocity field. More rapidly rotating stars built somewhat stronger fields, whereas slower rotators hosted weaker fields. Although differential rotation was established in hydrodynamic simulations, the strong magnetic fields realized in most MHD cases acted to strongly quench those angular velocity contrasts. Despite the absence of any significant shear, the magnetic fields realized in the simulations had structure on a broad range of spatial scales, and included a substantial large-scale component. The large-scale field generation is attributed partly to the strong influence of rotation upon the slowly overturning flows realized in M-stars.

## SUMMARY

Our current picture of magnetic field generation, rotation, and stellar activity may be summarized as follows:

1. Rotation rates are available for a wide range of masses and ages. Measurements of *projected* rotation velocities extend far into the brown dwarf regime, but direct measurements of rotational periods are lacking at very low masses.
2. We observe a sharp break in rotation around the threshold where stars become fully convective. This probably indicates a breakdown of wind braking.
3. Magnetic field measurements as well as activity tracers like X-rays,  $H\alpha$ , and radio emission show no obvious break at the convection boundary. However, around spectral type M7 normalized activity strongly weakens and the relation between radio and X-ray emission breaks down.
4. Apparently, very low mass stars can have strong large-scale magnetic fields yet only little wind braking. This remains an unresolved problem.
5. A key for understanding spindown is a theoretical understanding of wind braking. However, it is still a challenge for magnetic stellar wind theory to reliably calculate the wind torque for a range of stellar parameters. Furthermore, the wind torque is affected by the mass loss rate, so it is very important that we get measurements of mass loss rates and continue to improve mass loss theory.



6. Efforts to theoretically understand magnetic field generation evolved from the solar dynamo to the larger class of stellar dynamos, in particular to fully convective ones in absence of a tachocline. First models successfully reproduce magnetic field generation, but it certainly is still a long way to understanding magnetic dynamos in very cool stars.

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